of their existence.

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Failure of the Allowed Assumption in the ϵ/β^+ Decays of ^{145g}Gd and ^{143g}Sm—Experimental Evidence for Interference Effects in Nuclear β Decay

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Anomalous ϵ/β^+ decay branching ratios for "hindered allowed" transitions (measured by $\gamma^{\pm}$-γ and x-γ coincidence techniques) have been found in ^{145g}Gd → ^{145}Eu(808.5-keV state) and ^{143g}Sm → ^{143}Pm(1173.2-keV state). These ratios exceed theoretical predictions by factors of 24 and 5, respectively. Thirteen additional ratios from these nuclei and ^{143}Eu agree with the predictions. This is the first conclusive evidence of the failure of the allowed assumption in nuclear β decay and of the presence of interference effects.

Numerous past measurements of ϵ/β^+ (electron-capture to positron) decay branching ratios[1-4] tend to support modern β-decay and weak-interaction theory. These measurements generally involved simple, fast allowed transitions and were quite difficult to perform inasmuch as only very small deviations from the theoretically predicted ratios were involved and are difficult to detect. With the discovery of parity nonconservation and the success of the universal $V-A$ interaction, most of the interest in measuring these ratios disappeared, and in recent years only a few additional values have been measured. Studies on ^{145g}Gd decay in this laboratory[5] indicated an anomalous branching ratio involving a highly hindered allowed transition. In this work we study this transition more thoroughly and report a similar anomaly in ^{143g}Sm decay. We then discuss some of the ramifications of our findings.

All activities discussed here were prepared with beams from the Michigan State University sector-focused cyclotron. ^{145g}Gd ($t_{1/2}=22.9$ min) was prepared by the reaction ^{144}Sm(^{3}He, $2n$) using a 20-MeV ^{3}He beam on a target enriched to 95.10% in ^{144}Sm. ^{143}Eu ($t_{1/2}=2.6$ min) was produced by ^{144}Sm(p, $2n$) using a 28-MeV p beam on similar targets, and its daughter ^{143g}Sm ($t_{1/2}=8.83$ min) was studied along with it.

The relative β^+ feedings were measured by the $\gamma^{\pm}$-γ triple coincidence method described by Kelly and co-workers.[6] Briefly, the two halves of an 8×8-in. NaI(Tl) split annulus were gated on the 511-keV $\gamma^{\pm}$ radiation indicative of a β^+ event and a third γ-ray coincidence was sought in a large Ge(Li) detector inside the annulus tunnel. A resolving time of 50 nsec and the triple-coincidence requirement made chance events very rate. The relative β^+ feedings to each level were inferred from the coincident γ-ray spectrum after correcting for γ-ray feeding from higher-lying levels. The high efficiency of the annulus (60% at 511 keV) caused significant chance summing of annihilation quanta with γ rays in coincidence with those detected in the Ge(Li) detector, so only levels de-exciting primarily through a single direct ground-state transition could be studied. Fortunately, the nuclei discussed here decay predominantly to levels de-exciting directly to the ground states.

Relative ϵ feedings were measured by an x-γ coincidence experiment. A 5-mm-thick planar Ge(Li) detector with 550-eV resolution at 122 keV was gated on the K x-ray region to indicate an ϵ event, and a large Ge(Li) detector was gated on γ rays tagging the ϵ-fed level. (The γ transitions in the nuclei studied here all have high enough energies to make x rays resulting from internal conversion negligible.) The data were listed, three addresses per event (E_x, E_γ, and time), and were sorted off-line with subtraction of the continuum from both the x-ray and time axes. The resultant coincident γ-ray spectra were analyzed to obtain the relative ϵ feedings. Final ϵ feedings were corrected for L capture.[7]

The two sets of intensities were normalized to each other for ^{145g}Gd decay by assuming the theoretical ratio for decay to the 1757.8-keV level, which was chosen because it is fast ($\log ft = 5.8$) and the statistics are excellent. These relative feedings are presented in Table I. (If the theoretical predictions were correct, the choice of transition for normalization should not be significant; however, had we chosen the transition to the 808.5-keV level for normalization, the total β^+ feeding would far exceed 100%.) The measured ϵ/β^+ branching ratios are compared in Table I with the values tabulated by Gove and Martin[8] for $Q_\epsilon = 5.3$ MeV.[9] The data can perhaps be best compared with theory by defining a "skew ratio" $R = (\epsilon/\beta^+)_{\text{expt}}/(\epsilon/\beta^+)_{\text{theor}}$. It is thus a measure of how much the ϵ branch is enhanced or the β^+ branch is suppressed. Agreement is generally good except for the transition to the 808.5-keV level, where R has a value of 24. A 20% excess is also seen in the transition to the 1041.9-keV level.

The ^{143g}Sm and ^{143}Eu decays are more difficult to study because of the short half-lives involved. Only total feedings and relative β^+ feedings were measured, so ϵ feedings were inferred from these. The measured ratios in Table I are normalized to theory for the transitions to the 1056.6-keV level of ^{143}Pm and to the 1107.2-keV level of ^{143}Sm. Q_ϵ was assumed to be 3.32 meV for ^{143g}Sm decay[10] and 5.5 MeV for ^{143}Eu decay.[11] Again, agreement is good except for the transition to the 1173.2-keV level of ^{143}Pm, where the experimental ϵ/β^+ exceeds the theoretical one by a factor of 5.

The excellent agreement of most of the data with theory makes the exceptions stand out quite strongly. They are not easy to explain away. For

TABLE I. ϵ/β^+ branching ratios for ^{145g}Gd, ^{143g}Sm, and ^{143}Eu decays.

	Energy[a] (keV)	Q_ϵ (MeV)	ϵ(tot)/β^+ experimental	ϵ(tot)/β^+ [b] theoretical	Skew ratio R (expt/theor)
^{145g}Gd	808.5	4.5	10.7 ±2.0	0.45	24
	1041.9	4.3	0.72 ±0.05	0.60	1.2
	1757.8	3.5	≡1.17 ±0.05 [c]	1.17	1.0
	1880.6	3.4	1.34 ±0.05	1.37	0.98
	2494.8	2.8	3.07 ±0.5	3.39	0.91
	2642.2	2.7	4.70 ±0.5	4.41	1.07
^{143g}Sm	1056.6	2.26	≡9.7 ±0.7 [c]	9.7	1.0
	1173.1	2.15	63 ±10	13	4.9
	1403.1	1.92	35 ± 5	29	1.2
	1515.0	1.80	30 ± 7	49	0.61 [d]
^{143}Eu	1107.2	4.4 [e]	≡0.51 ±0.06 [f]	0.46	1.11
	1536.7	4.0	0.62 ±0.06	0.69	0.90
	1565.9	3.9	0.69 ±0.15	0.72	0.96
	1715.1	3.8	0.75 ±0.17	0.83	0.90
	1912.6	3.6	1.07 ±0.11	1.02	1.05

[a]Only the ratios for the most significantly fed levels are included in this table.
[b]Values from Ref. 8.
[c]ϵ/β^+ ratios are normalized to this transition.
[d]An error of only 100 keV in the reported decay energy would bring this value in line with theory without significantly affecting the fit of the rest of the data.
[e]The total available decay energy for ^{143}Eu was chosen as 5.5 MeV to obtain the best comparison with the theoretical values.
[f]The ^{143}Eu experimental ratio normalization was adjusted slightly to give the best and most consistent agreement with theory.

example, extreme care was taken to insure that the β^+'s were completely annihilated within the source package in the annulus tunnel, so effects such as incomplete annihilation cannot be the explanation. The γ transitions associated with the levels that receive the anomalous β decay are all well understood from previous studies[5,12,13] and should not be delayed, so this cannot be the explanation either. This was also seen in the time-to-amplitude converter spectra for ^{145g}Gd, where all the transitions were prompt. Errors in the decay schemes must be small, as virtually 99% of the γ-ray intensity is firmly placed in each. Corrections for L capture are straightforward and affect the relative feedings only slightly.

The implications of these anomalous ϵ/β^+ branching ratios may be quite significant. Close observation of the ^{145g}Gd and ^{143g}Sm anomalies indicates that they are not random cases but instead particularly hindered allowed transitions of a similar nature. (The "fast" transitions in the decays of these nuclei have been shown[5,10] to lead to three-quasiparticle states.)

Actually, our arguments do not hinge on the detailed nature of these transitions—for the purposes of what follows they might just as well be considered "fast" transitions between states of unknown structure. It was also shown by Biryukov and Shimanskaya[15] that the transition to the ground state of ^{143}Pm gives the predicted ratio. On the other hand, the anomalous transitions of ^{145g}Gd to the 808.5-keV state in ^{145}Eu and of ^{143g}Sm to the 1173.1-keV state in ^{143}Pm both proceed through the $\pi s_{1/2}$ states of the daughters. These hindered transitions are of the (over-simplified) form

$$(\pi d_{5/2})^2(\nu s_{1/2})^{-1} \to (\pi s_{1/2})(\nu s_{1/2})^{\text{full}}, \quad \log ft = 7.1,$$

for ^{145g}Gd decay and

$$(\pi d_{5/2})^2(\nu d_{3/2})^{-1} \to (\pi s_{1/2})(\nu d_{3/2})^{\text{full}}, \quad \log ft = 6.4,$$

for ^{143g}Sm decay. As written, these are complex multiparticle decays and rearrangements and may very well proceed through small components of the wave functions. The important fact, however, is that the anomalous ϵ/β^+ branching ratios occur in these *hindered allowed* transitions. (It should be emphasized that the basic characters of all of these shell-model states are well known from a combination of decay-scheme, atomic-beams,[16] and single-particle-transfer[17-19] studies; these *are* indeed allowed transitions.) The transitions to the $\pi d_{3/2}$ states at 1041.9 keV ($\log ft = 6.7$) in ^{145}Eu and 1403.1 keV ($\log ft = 6.3$) in ^{143}Pm are also complex but to a lesser extent. They display smaller anomalies ($\approx 15\%$) in the ϵ/β^+ branching ratios.

The transition amplitude squared for β decay can be written[20]

$$h_{fi} = \xi(1 \pm b\langle W\rangle^{-1})$$

for $e^{\mp}$ decay, where

$$\xi = [|C_S|^2 + |C_V|^2](\int 1)^2 + [|C_A|^2 + |C_T|^2](\int \sigma)^2 + [|C_A|^2 + |C_P|^2](\int \gamma_5)^2 + [|C_S|^2 + |C_T|^2](\int \alpha)^2$$

and

$$b\xi = 2[C_S C_V(\int 1)^2 + C_A C_T(\int \sigma)^2 + C_A C_P(\int \gamma_5)^2 + C_S C_T(\int \alpha)^2].$$

Here C_S, C_V, C_A, C_T, and C_P are the coupling constants for the scalar, vector, axial-vector, tensor, and pseudoscalar interactions, respectively (with terms for odd and even couplings implicit), and the matrix elements have their customary definitions. The ϵ/β^+ branching ratios give evidence of interference terms because of the opposite signs of b in the expression for h_{fi}. This can be seen in the equation for the electron-capture to positron transition-probability ratio,

$$\lambda_K/\lambda_+ \approx \tfrac{1}{2}\pi(W_0 + 1)^2 g_K^{\,2}(1 + b)/(1 - b\langle W^{-1}\rangle).$$

In the allowed assumption $\int \gamma_5$ and $\int \alpha$ are considered to be much smaller than $\int 1$ and $\int \sigma$ because they are proportional to v/c (≈ 0.1)—thus, they are ignored.

The fact that the anomalous ϵ/β^+ branching ratios occur for hindered transitions brings into question the allowed assumption. If the allowed matrix elements $\int 1$ and $\int \sigma$ are small, this does not necessarily mean that the higher order corrections are also reduced. It is conceivable that in some cases the "correction" terms could be considerably larger than the allowed terms. In such cases the higher order terms will lead to *VA* interference, which will give considerably larger ϵ/β^+ ratios than those predicted for allowed transitions. This is borne out in measurements of ϵ/β^+ ratios in second-forbidden unique transitions where the ratios are as much as 6 times the corresponding allowed values.[21] Unfortunately, as many as six matrix elements can contribute to our anomalous transitions, so the net effect cannot be predicted. Calculations are currently underway in this laboratory to estimate better the relative contributions of higher order matrix elements.

As long as higher order matrix elements are possibly important, the C_AC_P interference term must also be considered. The pseudoscalar coupling has never been adequately eliminated for β decay, and this may be a good way to test it. The AP interference will also lead to larger ϵ/β^+ branching ratios than predicted for allowed decay, and it is more importantly a critical test of two-component neutrino theory and exclusively left-handed particles. Measurements of β helicity and possibly spectrum shapes on hindered transitions should provide a sensitive test for such interference.

In conclusion, we have found solid experimental evidence for ϵ/β^+ branching ratios for hindered allowed transitions that are much larger than theory would predict. Thus, allowed β-decay theory is inadequate to explain these transitions, and large interference effects are indicated. Other hindered transitions should prove to be good places to search for such effects, and helicity and shape measurements should provide more insight into the exact nature of the interference.

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